Wall-Resolved Large Eddy Simulations of Separated Flows

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Work performed in collaboration with Dr. Mujeeb Malik
Motivation

• Flow separation is an important problem

• Separation leads to increased drag, stall and system performance loss

• Separated flows are very difficult to predict
Motivation

- NASA wall-mounted hump problem shows the failure of Reynolds-Averaged Navier-Stokes (RANS) turbulence models in separated flows
Motivation

- LES or DNS are of higher fidelity than RANS but very challenging at high Reynolds numbers.
- A viable strategy for high Reynolds numbers is the wall-modeled LES (WMLES) approach.
- WMLES attempts to model the near-wall region to ease the computational cost.
- WMLES has shown mixed success so far.
- Success/failure of WMLES strongly depends on the robustness of wall model.
- Hard to assess the true performance of some wall models available in literature.
- Critical information, such as skin friction predicted by WMLES, is not always provided.
Motivation

• We have been working on wall-resolved LES (i.e. no wall model) at high Reynolds numbers
• Such simulations are very rare
• Our goal is to obtain good-quality reliable data
• Such data can guide the development of improved/new wall models for WMLES
• Improved WMLES with better wall models can provide predictions with much faster turnaround
• Have encountered some issues along the way
• Will discuss those issues today
• Will also show results from the completed LES
What is wall-resolved LES?

- A wall-resolved LES is a turbulence simulation whose grid resolution *approaches* DNS-level grid resolution in the near-wall region.
- For example, for a flat-plate turbulent boundary layer, typical DNS resolutions in wall units are:
  - Streamwise resolution: $\Delta_x^+ \approx 10 - 15$
  - Spanwise resolution: $\Delta_z^+ \approx 5 - 10$
  - Wall-normal resolution on the wall: $\Delta_y^+ \leq 1$

- For wall-resolved LES:
  - Near-wall $\Delta_x^+, \Delta_z^+$ can be a factor of about 2 coarser than DNS
  - $\Delta_y^+ \approx 1$ on the wall
Numerical Methods for LES Flow Solver

- Discretized compressible Navier-Stokes equations in generalized curvilinear coordinates
- High-order compact finite difference schemes
- High-order spatial filtering for numerical stability
- Explicit and implicit time advancement schemes
- Multi-block and overset grid capability to handle complex geometry
- Parallelization based on domain-decomposition
- Artificial dissipation for shock-capturing
- Can be run in Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) modes
- Implicit or explicit subgrid-scale (SGS) models
- Methodology in development for over a decade
Parallel Speedup on IBM Blue Gene/Q (Fixed Total Problem Size)

DNS on 1.8 billion grid points total

96% efficiency on 524,288 cores
Problem of Interest: Flow Separation over Wall Hump

- End plates are used to improve two-dimensionality
- End plates also create a blockage effect
Spanwise-Periodic LES Schematic

- LES does not include end plates but assumes spanwise periodicity instead.
Issues Encountered

- Three important issues were encountered:
  - Turbulent inflow generation upstream of the hump does not work well
  - Reynolds number is quite high: Significant grid resolution is needed in order to perform a proper wall-resolved LES
  - Uncertainty in experimental inflow conditions:
    - Experimental upstream skin friction does not match the value corresponding to the stated inflow $Re_\theta$ (momentum thickness Reynolds number)
First Issue: Turbulent Inflow Generation

• Inflow generation technique is based on the rescaling-recycling technique
• This method assumes zero pressure-gradient

• The zero-pressure-gradient assumption turns out to be invalid upstream of the hump
First Issue: Turbulent Inflow Generation

- The figure below shows some trapped waves in front of the hump, which bounce up and down

Wave impingement on lower wall creates local adverse/favorable pressure gradients, violating the zero-pressure-gradient assumption
First Issue: Turbulent Inflow Generation

- To get around this issue, we run the LES simultaneously in two zones:
- **Zone 1**: Turbulent boundary layer developing on a flat plate under zero-pressure gradient
- **Zone 2**: Flow over wall-mounted hump
- **Zone 1** is completely independent of **Zone 2**
- An instantaneous plane extracted from **Zone 1** is introduced as the inflow condition for **Zone 2**
- Turbulent boundary layer injection is done at about 2 chord lengths upstream of the hump
Second Issue: Grid Resolution

- A proper wall-resolved LES requires significant number of points at high Reynolds number
- Near-wall grid resolution is very important for getting the correct skin friction
- To get the skin friction right for the flat plate, the code needs: \( \Delta_x^+ \approx 25, \Delta_z^+ \approx 12.5, \Delta_y^+ \approx 1 \)
- DNS-level resolution: \( \Delta_x^+ \approx 10 - 15, \Delta_z^+ \approx 5 - 10 \)
- Coarser resolutions under-predict skin friction
- It is prohibitively expensive to maintain these \( \Delta_x^+ \) and \( \Delta_z^+ \) until the boundary layer edge
- A reasonable compromise is to use a fine resolution grid near the wall and switch to a coarser grid away from the wall
Second Issue: Grid Resolution

- We keep $\Delta^+_x \approx 25$, $\Delta^+_z \approx 12.5$ until $y^+ \approx 200$ and then coarsen the grid by a factor of 2 in both streamwise and spanwise directions.
- We use overset grids for this purpose.
Snapshot of Turbulent Boundary Layer on Overset Grids
• In related papers, experimentalists state that:
  inflow \( Re_\theta \approx 6800 - 7200 \) at \( x/c \approx -2.14 \)
• The following figure is from the skin friction measurement paper (by Naughton, Viken and Greenblatt, *AIAA Journal*, 2006):

![Graph showing skin friction measurements](image)

• From this figure, \( u_\infty/u_\tau \approx 26.431 \) or \( u_\tau/u_\infty \approx 0.0378 \): This corresponds to \( Re_\theta \approx 5000 \)
Wall-Resolved LES Details

- Wall-resolved LES with 300 million point total
- $Re_c = 936,000$, Mach number = 0.1
- Spanwise-periodic domain with a size of 0.2c
- Flat-plate grid resolution on the wall:
  \[ \Delta^+_x \approx 25, \Delta^+_z \approx 12.5, \Delta^+_y \approx 1 \]
- $\Delta^+_x$ and $\Delta^+_z$ are coarsened by a factor of 2 at around $y^+ \approx 200$ on the flat plate
- Similar grid strategy applied for the hump
- Vreman’s constant-coefficient SGS model
- A turbulent boundary layer at $Re_\theta \approx 5000$ is injected upstream of the hump
- $\Delta t u_\infty / c = 2.5 \times 10^{-5}$ with a max CFL of 16.5
- Gathered time-averaged data over $10c/u_\infty$
Simulation Run Time

- Using 7200 “dedicated” Intel Ivy Bridge cores on NAS Pleiades, the simulation would take about 7.5 days to compute $20c/u_\infty$
- Note that we have a compressible flow solver and the Mach number is 0.1
- If the Mach number was 0.3, the simulation would take $7.5/3 = 2.5$ days
- Because of heavy load on NAS, the simulation is performed as multiple consecutive runs using fewer core counts
Thin Boundary Layer at around $x/c = 0.5$
Near-Wall Grid at around $x/c = 0.5$
Boundary Layer Separation on Hump
Near-Wall Grid in Separated Region
Complex Structure of Separated Flow
Pressure Coefficient Distribution

- Experiment with end plates
- Experiment without end plates
- Wall-resolved LES

![Graph showing pressure coefficient distribution](image-url)
Skin Friction Coefficient Distribution

- Experiment with end plates
- WRLES, upstream Re$\theta = 5000$
Observations from $C_f$ Plot

- Reasonable agreement with experiment
- The peak $C_f$ region in the LES seems a bit under-predicted relative to the experiment
- Differences may possibly arise from:
  - Uncertainty in upstream conditions
  - End-plate effects which cannot be captured in a spanwise-periodic calculation
- To see the effect of the upstream $Re_\theta$ on the peak $C_f$ region and separated flow, LES was repeated with an upstream $Re_\theta \approx 3000$
- The upstream $Re_\theta$ is lowered to 3000 in order to increase the upstream skin friction
- Same grid and time step as before
- Gathered time-averaged data over $10c/\bar{u}_\infty$
Effect of Upstream $Re_\theta$ on $C_f$

- Experiment with end plates
- WRLES, upstream $Re_\theta = 5000$
- WRLES, upstream $Re_\theta = 3000$
Flow Separation and Reattachment

- With $Re_\theta = 3000$, the peak $C_f$ region moves closer to the experiment, but there is greater discrepancy in the separated region.

- In the experiment:
  - Flow separates at $x/c \approx 0.665$
  - Flow reattaches at $x/c \approx 1.110$

- In the LES:
  - Both $Re_\theta$ cases separate at $x/c \approx 0.659$
  - For $Re_\theta = 5000$, flow reattaches at $x/c \approx 1.095$
  - For $Re_\theta = 3000$, flow reattaches at $x/c \approx 1.078$

- Next slides provide mean velocity and Reynolds stress profiles at $x/c = 0.65, 0.8, 0.9, 1, 1.1, 1.2, 1.3$
Streamwise Velocity with $Re_\theta = 5000$
Streamwise Velocity with $Re_\theta = 3000$
Vertical Velocity with $Re_\theta = 5000$
Vertical Velocity with $Re_\theta = 3000$
Reynolds Stress $\overline{u' u'}$ with $Re_\theta = 5000$
Reynolds Stress $\overline{u' u'}$ with $Re_\theta = 3000$
Reynolds Stress $\overline{v'v'}$ with $Re_\theta = 5000$
Reynolds Stress $\overline{v'v'}$ with $Re_\theta = 3000$
Reynolds Stress $\overline{u'v'}$ with $Re_\theta = 5000$
Reynolds Stress $\overline{u'v'}$ with $Re_\theta = 3000$
Observations and Ongoing Work

- Upstream boundary layer has some effect on the separated flow and reattachment point.
- Good overall agreement between the LES with $Re_\theta = 5000$ and experiment.
- We are re-running the LES with upstream $Re_\theta \approx 7000$.
- We plan to perform more detailed analysis of LES data.
- We are exploring the use of GPUs to accelerate the computations.
Next Problem: Transonic Shock-Induced Flow Separation on Axisymmetric Bump

- Very common problem in transonic flight
- We estimate 2 billion grid points for LES of the NASA experiment by Bachalo and Johnson
- Need 40,000 cores for 12 days of run time
- Hope to access DOE computers for this work